IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

OIPE IAP56 JUL 27 2006 PATENT & TRADEMARK OFFICE

In re application:	)	Atty. Docket No.: Sezerman
Omur M. Sezerman	)	Examiner: Leonidas Boutsikaris
Application No.: 10/632,111	)	Art Unit: 2872
Filed: 08/01/2003	)	
For: MICROSTRUCTURING OPTICAL WAVE GUIDE DEVICES WITH FEMTOSECOND OPTICAL PULSES	)	

SUBMISSION OF PRIORITY DOCUMENT

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Sir:

Pursuant to the provisions of MPEP 201.14(a)(2), Applicant hereby submits a certified copy of the priority document for the above-identified application, this being Canadian Patent Application No. 2,396,831 filed August 2, 2002. Since the issue fee has already been paid for the subject application, a check in the amount of $130.00 is attached to cover the fee under 37 CFR 1.17(i).

The Commissioner is hereby authorized to charge any deficiencies in fees or credit any overpayments to Deposit Account 10-1213.

Respectfully submitted,

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July 27, 2006

Repln. Ref: 07/31/2006 MBEYENE2 0018295700
DA#:101213 Name/Number:10632111
FC: 9204 $130.00 CR

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Specification as originally filed, with Application for Patent Serial No: **CA 2396831**, on August 2, 2002, by **FEMTONICS CORPORATION**, assignee of Omur M. Sezerman, Kenneth O. Hill, R.J.Dwayne Miller, Michael Armstrong and Shujie Lin, for "Microstructuring Optical Wave Guide Devices with Femtosecond Optical Pulses".

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Canada

(CIPO 68)
31-03-04

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MICROSTRUCTURING OPTICAL WAVE GUIDE DEVICES WITH FEMTOSECOND OPTICAL PULSES

FIELD OF INVENTION

The invention relates to the creation of permanently altered refractive index zones in glass, including optical waveguides and optical fibers, using the focussed light output of ultrafast pulsed lasers, and to all-fiber devices incorporating such zones exhibiting permanently altered refractive index characteristics.

DESCRIPTION OF THE RELATED ART

All-fiber optical devices have many practical advantages, including low loss, ease of coupling with other fibers, polarization insensitivity, low temperature coefficient, and simple packaging, which make them attractive and low-cost solutions in the optical telecommunications and other industries. All-fiber devices rely on refractive index variations for their functions, and various methods for making permanent refractive index changes have been used in the past. Older methods have relied on exposing photosensitive optical fiber, such as Germanium doped optical fiber, to ultraviolet light to produce refractive index changes in the glass.

A more recent method relies on the use of ultrafast pulsed lasers for producing very high intensity light and the resulting non-linear optical effects which are responsible for the refractive index modification phenomenon, see for example, US Patent No. 6,297,894 to Miller, et al. This method does not need photosensitive optical fiber. It works with many common optical fibers, including conventional telecommunications, sensor and amplifier fibers as well as undoped optical fibers, and photosensitive optical fibers.

Ultrafast pulsed lasers allow moderate pulse energies to produce very high peak pulse intensities. Focussing the laser beam with lenses or mirrors achieves peak pulse intensities of 10^{10} W/cm^2 and higher in the focal region, which is above the threshold for inducing permanent refractive index changes.

SUMMARY OF THE INVENTION

The present invention is directed to the creation of zones of permanently altered refractive index characteristics, through in glass, particularly in optical waveguides and optical fibers. Such zones in which the refractive index has been permanently altered are created in glass using a very high intensity laser beam which is produced by focussing the light output from an ultrafast pulsed laser at a predetermined target region in the glass. The preferred laser for this invention is a Ti:Sapphire amplified, frequency-doubled Erbium-doped fiber amplifier, providing light pulses of approximately 100 femtosecond duration, each with an energy of between about 1 nanojoule and 1 millijoule, and preferably at a pulse repetition rate of between 500 Hz and 1 GHz.

The altered zones in optical waveguides and fibers have a threefold effect. First, refractive index changes in core and in the core-cladding boundary region, and possibly in the evanescent region in the cladding, allow light propagating in the core to escape to the cladding. Second, the altered zone itself acts as an optical waveguide, allowing light propagating in the core to escape to the altered zone. Third, the surface of a suitably oriented altered zone acts as a reflecting surface. These three effects can be used for making all-fiber devices.

An all-fiber attenuator, an all-fiber tap, and an all-fiber polarimeter will be described hereinafter. All-fiber attenuators utilizing the three effects mentioned above scatter light out of the core, thereby achieving adjustable losses of 0 - 40 dB which can be set in 0.1dB increments. All-fiber taps can be made with a typical tap ratio of 1%. All-fiber polarimeters utilize the reflecting surfaces of altered zones that are oriented at Brewster angles to reflect s-polarized light out of the core. By using four of such altered zones which are positioned along the length of an optical waveguide or fiber, with azimuthal angles spaced 45 degrees apart, all four Stokes parameters that completely specify the polarization state of the light propagating in the core can be measured. The optical return loss for all-fiber devices made with altered zones is greater than 40 dB.

The creation of such altered zones in a fiber eliminates the need for precision alignment at the input and/or the output of the fiber into another fiber. This greatly

reduces the insertion losses and the cost of the all-fiber device.

In summary, the present invention may be generally considered to provide a method of creating a zone of permanently altered refractive index characteristics in an optical waveguiding device made of glass material having at least one core, using a beam which is generated by a focussed pulsed laser light source having:(i) a wavelength greater than the ultraviolet absorption edge of the glass material; (ii) a pulse width of less than 1 picosecond, and a pulse energy of between 1 nanojoule and 1 millijoule; and (iii) a peak pulse intensity within a defined focal region; comprising the steps of: (a) aligning the laser beam focal regions with a defined target region within the waveguiding device; and (b) operating the laser light source with the peak pulse intensity thereof at at least the threshold for inducing permanent refractive index changes in the waveguiding device at the target region.

The invention may also be considered to encompass an optical waveguiding device having a core, a cladding, and at least a single zone therein at which the refractive index characteristics of the waveguiding device have been permanently altered, whereby the altered waveguiding device can serve as an attenuator, a polarimeter, or an optical tap.

DESCRIPTION OF THE INVENTION

A suitable type of ultrafast pulsed laser for producing a write beam according to this invention is a laser emitting pulses each with a duration of less than 1 picosecond, preferably between 2 and 200 femtoseconds, and more preferably about 100 femtoseconds, and a pulse energy between 1 nanojoule and 1 millijoule. The laser can be operated using single pulses or with a variable pulse repetition rate between 500 Hz and 1 GHz, preferably between 1 kHz and 100 MHz. The wavelength of the light must be greater than that of the ultraviolet absorption region of the glass material in which a refractive index change is to be made. In the case of standard fused silica glass, which is commonly used in the manufacture of optical waveguides and fibers, the wavelength of the light must therefore be greater than 200 nanometers. The laser for this application is typically based on a Ti:Sapphire, Chromium doped, or Erbium doped solid state mode-locked laser oscillator. Depending on the energy of the light

pulses required for exposing the glass materials, the light pulses from the laser oscillator may also be amplified through an amplifier stage based on one or more of similar solid state laser media with broadband gain. The output from either the laser oscillator or the amplifier may also be used to pump an optical parametric amplifier to generate the light pulses used to expose the glass materials.

A preferred laser for this invention is therefore a Ti:Sapphire amplified, frequency-doubled Erbium doped fiber amplifier, providing light pulses of approximately 100 femtosecond duration each with an energy of between 1 nanojoule and 1 millijoule at a pulse repetition rate of between 1 kHz and 100 MHz. The laser light source beam diameter should be in the range of >0.1 to about 10mm; the focal length should be in the range of about 1mm to about 30cm; and the numerical aperture of any lens or mirror utilized therewith should be in the range of about 0.05 to about 1.3.

The laser light can be focussed with a lens or a mirror, thereby creating very high intensity light in the focal region. At peak pulse intensities at or above the threshold for inducing permanent refractive index changes, which is about 10^{10} W/cm^2, the focal region can be used as a write beam. By moving the write beam relative to the glass material to be written into, the microstructure of the glass can be restructured to create a defined zone having permanently altered refractive index characteristics. The altered zone can be created by pin-point focussing, or line focussing, of the beam at a target region in the workpiece or by sweeping the write beam over the target region. The altered zone can be created in a variety of optical waveguides and fibers, including any glass substrate with an embedded optical waveguide, conventional optical fibers, polarization maintaining fibers, optical fibers with Germanium enriched core, optical fibers with rare-earth dopants either in the core or in the cladding region, hydrogen loaded optical fibers, optical waveguides and fibers having more than one core, such as the waist region of a taper coupler, optical waveguides and fibers having more than one cladding, such as W-fibers, holey fibers (photonic crystal fibers), fiber Bragg gratings, photonic bandgap materials and other optical waveguides and fibers with complicated refractive index profiles.

One method for accurately creating altered zones in optical waveguides or fibers

having a core has the optical waveguide or fiber mounted on a high precision stage with better than 1 micron positioning accuracy. The focal region of the laser beam is aligned with the core using the following alignment procedure. The peak pulse intensity of the laser source is first set at low power to avoid making permanent refractive index changes to the glass during the alignment procedure. The laser beam is oriented at a desired angle relative to the longitudinal axis of the core, depending on the desired shape of the altered zone to be created. The focal region is scanned over the optical waveguide or fiber, and a photomultiplier tube is used to detect the amount of multiphoton fluorescence from the core. The location of the focal region is optimally aligned to the location of the core, when the detected amount of multiphoton fluorescence is at a maximum. Using the optimum alignment as a spatial reference, the focal region is then moved, after the peak pulse intensity has been increased to at least the threshold for inducing permanent refractive index changes, to create altered zones in the optical waveguide or fiber. The laser beam can be directed towards the workpiece 'from above' or 'from below', referring to a setup wherein the focal region of the laser source is initially positioned above or below the optical waveguide or fiber mounted in the precision stage. When directing the laser beam 'from above', the focal region is initially positioned above the optical waveguide or fiber, and moved downwards. When directing the laser beam 'from below' the focal region is initially positioned below the optical waveguide or fiber and moved upwards.

Using two or more laser sources, or a single source whose output beam is split into two or more beams, allows for collision of the beams, i.e. the focal regions of the multiple beams intersect in the glass material such that the combined peak pulse intensity reaches threshold only in the intersect or target region, thereby improving the localization of the refractive index change. The alignment procedure is similar to the above, only the maximum fluorescence is now indicative of the focal regions being aligned relative to each other and to the core. The focal regions are then either moved in unison for creating the altered zone, or the workpiece is moved with respect to the focal regions.

The use of multiple beams for creating the altered zones in the workpiece should provide better resolution and potentially a more homogeneous zone of altered

refractive index characteristics. Also, with multiple beams there is the potential to take advantage of interferometric effects to create specific types of altered zones, including for example, micro-gratings.

According to this invention, using one or more altered zones created in one or more positions and orientations in an optical fiber, a number of all-fiber devices can be made, including all-fiber attenuators, all-fiber taps, and all-fiber polarimeters which will described in the following.

While the foregoing describes methods using one or more moving beams or a moving workpiece, it should be understood that altered zones can be created without relative movement between the beam(s) and the workpiece as long as the focal region of the beam(s) can be located with pin-point accuracy at a predetermined target region within the workpiece.

An all-fiber attenuator is an optical waveguide or fiber which attenuates light propagating in the core. The attenuation is achieved by letting a portion of the light escape from the core which is in turn achieved by creating an altered refractive index zone at the escape location. The altered zone may be created substantially perpendicularly or at an acute angle to the longitudinal axis of the optical waveguide or fiber. The altered zone may include refractive index changes in the core-cladding boundary region, in the evanescent region in the cladding, and/or in the core of the optical waveguide or fiber. Refractive index changes in the core-cladding boundary region and in the evanescent region in the cladding lead to a coupling between the core and the cladding propagation modes and therefore to part of the light propagating in the core escaping into the cladding. Refractive index changes in the core perturb the light propagating in the core and part of it is scattered out of the core via two escape mechanisms. The first escape mechanism scatters part of the light out of the core by coupling it to the waveguide formed by the altered zone which is oriented at an acute angle to the longitudinal axis of the optical waveguide or fiber. The second scattering mechanism scatters part of the light out of the core by way of Fresnel reflection at the surface of the altered zone which is oriented at an acute angle to the longitudinal axis of the optical waveguide or fiber. The surface of a suitably oriented altered zone acts therefore as a reflecting surface.

The achievable attenuation loss is between 0 - 40 dB depending on the length of exposure time for making the altered zone, the light pulse energy, the sweeping speed of the laser beam, the distance the write beam has been swept across the optical fiber, and the angle that the sweeping direction makes with respect to the longitudinal axis of the optical waveguide or fiber. Typically, losses due to refractive index changes in the evanescent region in the cladding are approximately 0.1 dB in magnitude, and losses due to refractive index changes in the core-cladding boundary region are 1 - 30 dB in magnitude.

In a preferred embodiment of an all-fiber attenuator, the loss can be accurately adjusted using a combination of loss induced with the refractive index changes in the core-cladding boundary region and loss induced with refractive index changes in the evanescent region in the cladding. At losses greater than 0.1 dB, the greater part of the loss can be induced with the refractive index changes in the core-cladding boundary region and fine adjustments to the loss in approximately 0.1 dB increments can be induced with refractive index changes in the evanescent region in the cladding.

In another embodiment of an all-fiber attenuator, the loss may be induced by sweeping the laser beam substantially parallel to the optical fiber and centred in the evanescent region in the cladding, in the core-cladding boundary region, or in the core. In this embodiment, typically the magnitude of the loss depends on the sweeping distance up to a loss of less than 1 dB for a single sweep, where the magnitude of the loss saturates for laser beam waist diameters of 10 - 20 micrometers. Within this limit, the loss can be adjusted by changing the length of the altered zone along the length of the optical waveguide or fiber.

When the loss has been induced by creating an altered zone at a small angle to the longitudinal axis of the optical waveguide or fiber, the achievable loss can be greater than 30 dB. Typically, even for such very high loss, the optical return loss is better than 40 dB, i.e. the intensity of light propagating in the core in the backward direction is more than 40 dB below the intensity of the light propagating in the core in the forward direction.

An all-fiber tap is an optical waveguide or fiber which couples a small portion of the light out of the core and out of the optical waveguide or fiber, which can then be

measured with an optical power detector such as a photodiode or a photomultiplier tube. In fact an optical tap can form the basis for a power monitor in which the detector is used to collect light from the tap and to send a signal indicative of power level to an appropriate information retrieval device.

With all-fiber taps light is coupled out of the core using similar altered zones as in the above described case of an all-fiber attenuator, although the portion of the light coupled out of the core in the case of an all-fiber tap is typically much smaller with a tap ratio of typically 1%. The all-fiber tap therefore allows for the monitoring of the amount of light propagating in the core by monitoring the amount of light coupled out of the optical waveguide or fiber at the expense of diverting only a small amount of light.

If the altered zone is oriented perpendicularly to the longitudinal axis of the optical waveguide or fiber then the light coupled out of the core is at a grazing angle to the surface of the optical waveguide or fiber, and index matching fluid can be used to avoid total internal reflection at the surface of the optical waveguide or fiber, and to allow the light to escape from the optical waveguide or fiber and be detected by an optical detector. If the altered zone is oriented at a sufficiently large angle to the longitudinal axis of the optical waveguide or fiber then index matching fluid can be omitted, since the light coupled out of the core may be at a larger angle than the critical angle for total internal reflection, thereby avoiding total internal reflection at the surface of the optical waveguide or fiber.

The optical return loss for all-fiber taps is greater than 40 dB.

An all-fiber polarimeter is an optical waveguide or fiber capable of measuring the polarization states of the light propagating in its core. To this end, a number of reflecting surfaces must be oriented substantially at a Brewster angle to the longitudinal axis of the optical waveguide or fiber, such that mainly s-polarized light will be reflected with negligible amount of p-polarized light reflection. Spacing the azimuthal angle of four reflecting surfaces along the length of an optical waveguide or fiber by 45 degrees allows for the measurement of all four Stokes parameters, thereby specifying the complete polarization state of the light propagating in the core. A prior art all-fiber polarimeter by Westbrook, Strasser, and Erdogan uses a blazed fiber

Bragg grating for each of the reflective surfaces (IEEE Photonics Technology Letters, Vol. 12, No. 10, pp. 1352 - 1354, October 2000).

An embodiment of an all-fiber polarimeter according to this invention implements each of the four reflective surfaces with an altered zone, taking advantage of the reflective properties of the surface of an altered zone. The Brewster angle of an altered zone depends on the pulse energy, the pulse width, the pulse repetition rate, the sweep speed, and the size of the waist of the write beam. A reflecting surface with a Brewster angle of 45 degrees which conveniently reflects s-polarized light in a direction perpendicular to the longitudinal axis of the optical waveguide or fiber with minimal contamination of p-polarized light. A $\lambda/2$ wave plate may be inserted between a pair of adjacent altered zones, such as the third and fourth altered zones, to distinguish between right and left circularly polarized light. To this end, a UV-induced $\lambda/2$ fiber wave plate as in the quoted IEEE reference may be used. With the $\lambda/2$ wave plate in the core, circularly polarized light will or will not be reflected by the fourth altered zone, depending on the direction of rotation of the E-vector of the light propagating in the core. The polarization axis of the $\lambda/2$ wave plate can be oriented either along or at a right angle to the s-polarized direction of the fourth altered zone.

Another embodiment of an all-fiber polarimeter uses two identical altered zones with the azimuthal angles spaced at substantially 90 degrees, and p-polarized light for the first reflecting surface is therefore s-polarized for the second reflecting surface. The light intensity of both polarization states in the fiber core may therefore be measured independently, although the full polarization state cannot be determined with only two reflecting surfaces. A slight deviation from the orthogonal azimuthal angles will balance the polarization dependence of the two swaths, thereby reducing polarization-dependent losses.

The return loss for all-fiber polarimeters is greater than 40 dB.

It should be noted that certain losses in an attenuator and that polarization dependent tapping in a tap can be compensated for by including at least two altered refractive index zones within the attenuator or tap, with the zones being oriented relative to each other to achieve the desired degree of compensation. Such zones could be created by sweeping the beam through the workpiece from, for example, left

to right, and then again (at the same relative angle) from top to bottom, possibly at the same location.

A person skilled in the art will now readily appreciate the flexibility and versatility of the disclosed methods for writing altered zones in glass. To give an example for the flexibility of the disclosed methods: variations of the methods include the use of two or more laser sources which are moved independently from each other rather than in unison. To give an example for the versatility of the disclosed methods: the methods can be applied to specialty optical fibers, as distinct from conventional telecommunications fibers, which will apparently produce other novel products in addition to the novel all-fiber products disclosed. Variations of the described embodiments are therefore to be considered within the scope of the invention.